Influence of neutron-skin thickness on the π^-/π^+ ratio in Pb + Pb collisions

Gao-Feng Wei,[1,2,*] Bao-An Li,[1,3,†] Jun Xu,[4,‡] and Lie-Wen Chen[5,6,§]

[1] *Department of Physics and Astronomy, Texas A&M University–Commerce, Commerce, Texas 75429-3011, USA*
[2] *School of Physics and Mechatronics Engineering, Xi'an University of Arts and Science, Xi'an, 710065, China*
[3] *Department of Applied Physics, Xi'an Jiao Tong University, Xi'an 710049, China*
[4] *Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China*
[5] *Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China*
[6] *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

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Within an isospin- and momentum-dependent transport model (IBUU11) using as an input nucleon density profiles from Hartree-Fock calculations based on a modified Skyrme-like (MSL) model, we study the influence of the uncertainty of the neutron skin thickness on the π^-/π^+ ratio in both central and peripheral Pb + Pb collisions at beam energies of 400 MeV/nucleon and 1000 MeV/nucleon. Within the current experimental uncertainty range of neutron skin in ^{208}Pb, while the neutron skin effect on the π^-/π^+ ratio is negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions especially at 400 MeV/nucleon. Moreover, we find that while the π^-/π^+ ratio is larger with a softer $E_{\mathrm{sym}}(\rho)$ in central collisions, above certain impact parameters depending on the size of the neutron skin, a stiffer $E_{\mathrm{sym}}(\rho)$ can lead to a larger π^-/π^+ ratio as most of the pions are produced at densities below the saturation density in these peripheral reactions. Therefore, a clear impact parameter selection is important to extract reliable information about the $E_{\mathrm{sym}}(\rho)$ at suprasaturation densities (size of neutron skin) from the π^-/π^+ ratio in central (peripheral) heavy-ion collisions.

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I. INTRODUCTION

The density dependence of nuclear symmetry energy $E_{\mathrm{sym}}(\rho)$ affects not only the structure of nuclei and neutron stars, such as the neutron skin in heavy nuclei and radii of neutron stars [1,2], but also their reaction dynamics, such as particle production in heavy-ion collisions [3–9] and emission of gravitational waves in spiraling neutron star binaries [10]. Thus, combining information from various laboratory experiments and astrophysical observations has the promise of mapping out accurately the still poorly known $E_{\mathrm{sym}}(\rho)$ in a broad density range [11,12]. In particular, effects of various observables from the size of neutron skin, pygmy dipole resonance, and dipole polarizability in heavy nuclei (see, e.g., Refs. [13–16]) to the neutron/proton [17] and π^-/π^+ [18] ratios in heavy-ion collisions have been found to be sensitive to the $E_{\mathrm{sym}}(\rho)$ at different densities. While significant progress has been made in constraining the $E_{\mathrm{sym}}(\rho)$ mostly around saturation density ρ_0 [19], much more work needs to be done to better determine the $E_{\mathrm{sym}}(\rho)$ at both subsaturation and suprasaturation densities. For an overview of the latest status of the field, we refer the reader to the webpages of the 2013 International Collaboration in Nuclear Theory Program on Nuclear Symmetry Energy [20] and the Third International Symposium on Nuclear Symmetry Energy (Nusym13) [21] as well as the very recent European Physics Journal A Topical Issue on Nuclear Symmetry Energy [22].

The size of neutron skin has long been identified as one of the most promising observables to fix the $E_{\mathrm{sym}}(\rho)$ around 0.1 fm^{-3}; see, e.g., Refs. [23–28]. However, the available data obtained mostly from hadronic probes suffer from large uncertainties. For example, the experimentally measured size of neutron skin in ^{208}Pb currently ranges from about 0.11 ± 0.06 fm from π^+-Pb scattering [29] to $0.33^{+0.16}_{-0.18}$ fm from the Parity Radius Experiment (PREX)-1 experiments using parity violating e-Pb scattering [30]. For a recent review, see, e.g., Ref. [31]. In particular, it was shown very recently within a relativistic mean-field model [32] that a neutron skin for ^{208}Pb as thick as $0.33 + 0.16$ fm reported by the PREX-I experiment [30] cannot be ruled out although most other studies have reported much smaller average values albeit largely overlapping with the PREX-I result within error bars. This situation has stimulated the renewed interest to experimentally measure model-independent sizes of neutron skins in medium and heavy nuclei. In this regard, it is interesting to note that the approved Calcium Radius Experiment and PREX-II experiments at the Jefferson Laboratory [33] are expected to provide more accurate values for the neutron-skin thickness in both ^{48}Ca and ^{208}Pb.

On the other hand, the π^-/π^+ ratio in heavy-ion collisions near the pion production threshold [18] is among the most promising tracers of nuclear symmetry energy at suprasaturation densities based on transport model simulations by several groups. Unfortunately, the theoretical results from different models are still inconsistent with each other, and

*wei.gaofeng@foxmail.com
†Corresponding author: Bao-An.Li@tamuc.edu
‡xujun@sinap.ac.cn
§lwchen@sjtu.edu.cn

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conclusions from comparisons with very limited data available remain rather controversial [34–38]. This situation certainly demands collective efforts by the community, among other things, to quantify theoretical uncertainties associated with various model assumptions and input parameters in transport model studies of heavy-ion collisions. As a useful step towards this goal, we investigate effects of the uncertainties of the neutron-skin thickness on extracting information about the high-density symmetry energy using the π^-/π^+ ratio in heavy-ion collisions within the latest version of an isospin- and momentum-dependent transport model (IBUU11) [39]. Because of the diverse predictions using various interactions and many-body theories, the neutron skins for colliding nuclei used in transport models vary significantly. We investigate here how the size of neutron skin may affect the π^-/π^+ signal of the $E_{\rm sym}(\rho)$ from central to peripheral heavy-ion collisions. This is an important issue because the charged pion ratio has the dual sensitivity to both the size of neutron skin and the density dependence of nuclear symmetry energy. The two are obviously interconnected. In fact, soon after the high-energy radioactive beams become available some 25 years ago, the pion production in peripheral nuclear reactions was proposed as a sensitive measure of the size of neutron skin in rare isotopes [40–42]. It is thus necessary to examine the influence of the uncertainty of neutron-skin thickness on the information of $E_{\rm sym}(\rho)$ we may extract from studying the π^-/π^+ ratio in heavy-ion collisions. As an example, we study the π^-/π^+ ratio in Pb + Pb collisions from central to peripheral impact parameters at beam energies of 400 MeV/nucleon and 1000 MeV/nucleon. We see that while the neutron-skin effect on the π^-/π^+ ratio is found negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions, especially at 400 MeV/nucleon. Moreover, although the π^-/π^+ ratio is larger with a softer $E_{\rm sym}(\rho)$ in central collisions, we found that above certain impact parameters, depending on the size of the neutron skin, a stiffer $E_{\rm sym}(\rho)$ can lead to a larger π^-/π^+ ratio as most of the pions are created at densities below the saturation density in these peripheral reactions.

II. NUCLEAR SYMMETRY ENERGY AND INITIALIZATION IN IBUU11

This study is carried out using the isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [43] of version IBUU11 [39]. To ease the following discussions, we briefly describe here the isospin- and momentum-dependent interaction (MDI) used in the IBUU11 and the nucleon density profiles with different sizes of neutron skins used in initializing the two colliding nuclei. The momentum dependence of both the isoscalar [44–48] and isovector [43,49–51] parts of the nuclear interaction is important in understanding not only many phenomena in intermediate-energy heavy-ion collisions but also thermodynamical properties of isospin-asymmetric nuclear matter [52–54]. The MDI mean-field potential for a nucleon with momentum $\vec{p}$ and isospin τ can be written as [49]

$$U(\rho,\delta,\vec{p},\tau) = A_u(x)\frac{\rho_{-\tau}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma(1-x\delta^2) - 8\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{-\tau} + \frac{2C_{\tau,\tau}}{\rho_0}\int d^3p'\frac{f_\tau(\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2} + \frac{2C_{\tau,-\tau}}{\rho_0}\int d^3p'\frac{f_{-\tau}(\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2}. \quad (1)$$

In the above, $\rho = \rho_n + \rho_p$ is the nucleon number density and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry of the nuclear medium; $\rho_{n(p)}$ denotes the neutron (proton) density, the isospin τ is 1/2 for neutrons and $-1/2$ for protons, and $f(\vec{p})$ is the local phase space distribution function. The expressions and values of the parameters $A_u(x)$, $A_l(x)$, σ, B, $C_{\tau,\tau}$, $C_{\tau,-\tau}$, and Λ can be found in Refs. [49,55], and they lead to the binding energy of -16 MeV, incompressibility 212 MeV for symmetric nuclear matter, and symmetry energy $E_{\rm sym}(\rho_0) = 30.5$ MeV at saturation density $\rho_0 = 0.16$ fm^{-3}, respectively.

The MDI mean-field potential comes from Hartree-Fock calculations using a modified Gogny force including a zero-range effective three-body interaction and a finite-range Yukawa-type two-body interaction [49,55,56]. The variable x is introduced to mimic different forms of the symmetry energy predicted by various many-body theories without changing any properties of symmetric nuclear matter and the value of $E_{\rm sym}(\rho_0)$. Shown in Fig. 1 are the $E_{\rm sym}(\rho)$ with $x = 1$ and $x = 0$. The density dependence of $E_{\rm sym}(\rho)$ around an arbitrary density ρ can be characterized by the slope parameter there

$$L_u \equiv 3\rho(dE_{\rm sym}/d\rho)_\rho, \quad (2)$$

where $u = \rho/\rho_0$. The softer (stiffer) $E_{\rm sym}(\rho)$ with $x = 1$ ($x = 0$) has a value of $L_1 = 16.4$ (62.1) MeV and $L_2 = -100.3$ (85.6) MeV, respectively. Due to the well-known isospin fractionation during heavy-ion collisions, a larger value of $E_{\rm sym}(\rho)$ at density ρ generally leads to a smaller isospin asymmetry there to lower the energy of the system. Since the density reachable depends sensitively on the impact parameter and the π^-/π^+ ratio is sensitive to the isospin asymmetry of

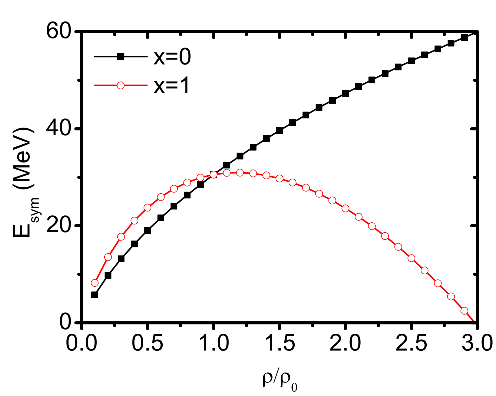

FIG. 1. (Color online) The density dependence of the symmetry energy.

the participant region, the dependence of the π^-/π^+ ratio on the $E_{\rm sym}(\rho)$ is expected to be affected by the impact parameter and the size of neutron skin.

To initialize transport models, it is necessary to know the nucleon density profiles for the two colliding nuclei. Ideally, one would like to use the same nuclear interaction to generate self-consistently the initial-state phase-space distributions within the reaction model itself. Indeed, this was done in some versions of the quantum molecular dynamics models. Another way of initializing nuclei is to use the Thomas-Fermi (TF) approach using the same interaction as for simulating their subsequent reactions; see, e.g., Refs. [57–59]. It is well known that the resulting density profiles depend on the interaction used. Practically, to the best of our knowledge, none of the available reaction models or the TF approach can describe properties of nuclei in their ground state as well as the microscopic and/or phenomenological many-body theories for studying nuclear structures. Thus, some reaction simulations use as an input nucleon density profiles predicted by nuclear structure models to initialize nucleons in coordinate space and then the local Thomas-Fermi approximation in momentum space [43]. The main problem of this approach is that the initial state may not be the ground state of the interaction used in the subsequent reactions. However, it allows one to easily separate effects on the final observables due to the initial state from those due to the reactions. One of the purposes of this work is to examine the relative effects of the neutron skin in initial nuclei and the symmetry energy at suprasaturation densities reached in central heavy-ion collisions on the charged pion ratio in the final state. The flexibilities of adjusting independently the size of neutron skin of colliding nuclei and the interaction used in the collision simulations are useful for our analyses in this work. Here, we initialize nucleons in phase space using neutron and proton density profiles predicted by Hartree-Fock calculations based on the MSL model [60,61]. The size of neutron skin S is normally measured by using the difference in the rms radii of neutrons and protons, i.e., $S \equiv \langle r_n{}^2\rangle^{1/2} - \langle r_p{}^2\rangle^{1/2}$. Shown in Fig. 2 are the density profiles corresponding to a neutron skin thickness S of 0.1 and 0.3 fm in ^{208}Pb. As one expects, the proton distributions are almost identical, while the neutrons distribute differently in the two cases considered.

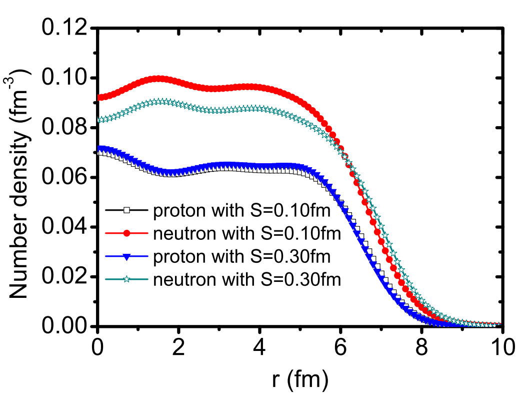

FIG. 2. (Color online) The neutron and proton density profiles for ^{208}Pb with neutron-skin thicknesses of 0.1 and 0.3 fm, respectively.

III. RESULTS AND DISCUSSION

We now present results of our studies in the following three subsections. Because the magnitude of isovector potentials is always much smaller than that of isoscalar potentials during heavy-ion reactions, isospin effects on reaction observables are generally very small. To exclude uncertainties of statistical nature from our physical considerations, we have performed large-scale calculations with 4×10^5 events in each case reported here. Thus, in most plots the statistical error bars are smaller than the plotting symbols except in very peripheral reactions.

A. Evolution of neutron skin and pion production during heavy-ion collisions

How long does the neutron skin persist at the initial value in the ground state of colliding nuclei and during heavy-ion reactions? How does that compare to the average time to produce a pion? Answers to these questions may help us better understand the interplay between the neutron skin of colliding nuclei and effects of the symmetry energy in nuclear reactions. They may also help evaluate the validity of our model assumptions. To answer these questions, we examine in Fig. 3 the evolution of the neutron skin initially set at $S = 0.1$ fm in the ground state of ^{208}Pb, and in the target/projectile during typical central (5 fm) and peripheral (9 fm) ^{208}Pb + ^{208}Pb collisions at beam energies of 400 and 1000 MeV/nucleon, respectively. It is seen that the initial neutron skin in the ground state lasts longer than the reaction time for the reactions considered, although a long-period and small-amplitude oscillation is visible. This level of stability of the ground state is good enough for the purpose of this study. For simulating nucleus-nucleus collisions, the centers of the two colliding nuclei are initially separated by a distance of $R_{\rm target} + R_{\rm projectile} + 3$ fm. The two nuclei then approach each other along their Coulomb trajectories before touching. In this case, the initial neutron skin persists for about 5 fm/c. Due to the Coulomb interactions, protons are pushed outward leading to negative S values in the later stage of the reaction.

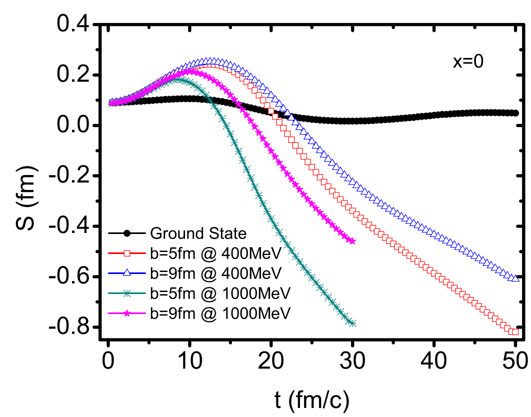

FIG. 3. (Color online) Evolution of the size of neutron skin initially set at 0.1 fm in the ground state of ^{208}Pb, and in the target/projectile in typical central and peripheral ^{208}Pb + ^{208}Pb collisions at beam energies of 400 and 1000 MeV/nucleon, respectively.

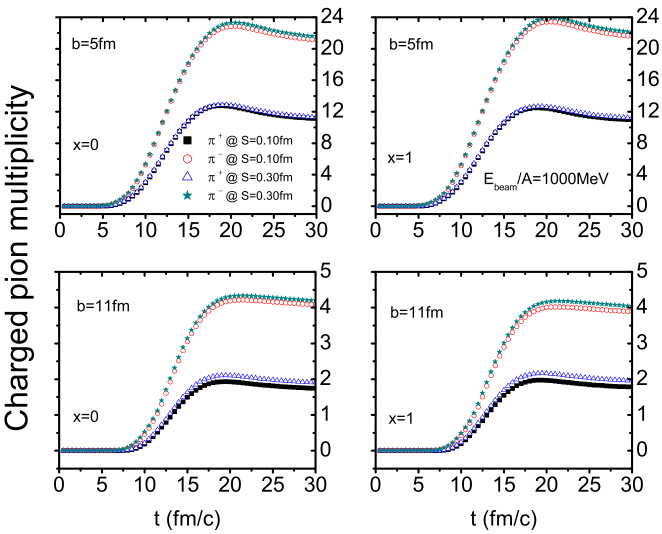

FIG. 4. (Color online) Evolution of the charged pion multiplicities in ^{208}Pb + ^{208}Pb collisions at impact parameters of 5 and 11 fm and a beam energy of 1000 MeV/nucleon, respectively.

Shown in Fig. 4 are the multiplicities of charged pions as a function of time in ^{208}Pb + ^{208}Pb collisions at impact parameters of 5 and 11 fm and a beam energy of 1000 MeV/nucleon, respectively. There are clear indications that the multiplicities of both π^- and π^+ increase as the initial size of neutron skin increases from 0.1 to 0.3 fm. However, the increase is appreciable only in very peripheral reactions. Unfortunately, effects of the symmetry energy on the pion multiplicities from comparing calculations with $x = 0$ and $x = 1$ are not so obvious. This naturally leads us to the need of looking at the ratio of charged pions in the next subsection.

B. Charged pion ratio as a probe of symmetry energy from central to peripheral reactions

Within the IBUU model for heavy-ion collisions up to about 1.5 GeV/nucleon, most pions are produced through the decay of $\Delta(1232)$ resonances. As discussed in detail in Ref. [18], the $(\pi^-/\pi^+)_{\rm like}$ ratio defined as

$$(\pi^-/\pi^+)_{\rm like} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+}, \tag{3}$$

is a good measure of the symmetry energy during heavy-ion collisions. At the final stage, all the Δ resonances will eventually decay and the $(\pi^-/\pi^+)_{\rm like}$ ratio naturally becomes the ratio of free pions, i.e., π^-/π^+. To see how the π^-/π^+ ratio in heavy-ion collisions depends on the impact parameter, the beam energy, and the $E_{\rm sym}(\rho)$ for a given neutron-skin thickness of 0.1 fm, we show in Fig. 5 the evolutions of the $(\pi^-/\pi^+)_{\rm like}$ ratio from midcentral to peripheral ^{208}Pb + ^{208}Pb collisions at a beam energy of 400 (left) and 1000 MeV/nucleon (right), respectively. For pion production, it is known that there is no obvious impact parameter dependence from head-on to midcentral heavy-ion reactions. Consistent with previous observations from various transport model calculations, the π^-/π^+ ratio

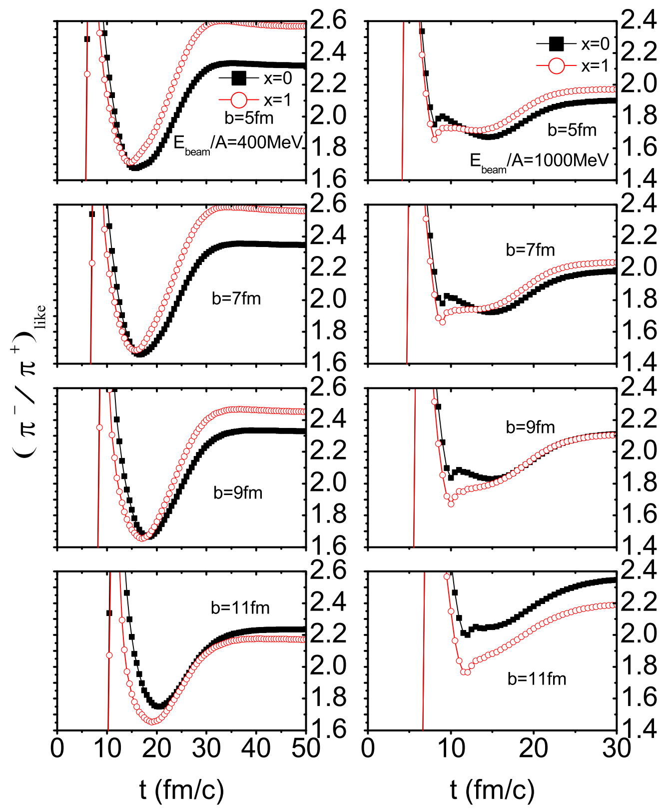

FIG. 5. (Color online) Evolution of the $(\pi^-/\pi^+)_{\rm like}$ ratio from midcentral to peripheral Pb + Pb reactions at beam energies of 400 (left) and 1000 MeV/nucleon (right). The x parameter is 1 (red [gray]) and 0 (black), and the size of neutron skin is 0.1 fm in all cases.

is larger and more sensitive to the $E_{\rm sym}(\rho)$ near the pion production threshold. One interesting new feature seen is that the dependence of the π^-/π^+ ratio on the $E_{\rm sym}(\rho)$ has a transition from midcentral to peripheral collisions. Namely, in central to midcentral collisions, a softer $E_{\rm sym}(\rho)$ with $x = 1$ leads to a larger π^-/π^+ ratio than the stiffer one with $x = 0$, whereas it is the opposite in peripheral reactions. This is because the average density of the participant region is significantly above ρ_0 in central to midcentral collisions, while it becomes lower than ρ_0 in peripheral collisions. In the latter case, a softer $E_{\rm sym}(\rho)$ gives a larger value of the symmetry energy and a less neutron-rich participant matter, resulting in a smaller π^-/π^+ ratio. This feature indicates that the sorting of events according to some effective impact parameter selection criteria is very important for extracting reliable information about the $E_{\rm sym}(\rho)$ from the π^-/π^+ ratio in heavy-ion collisions.

C. Interplay of neutron skin and symmetry energy on the charged pion ratio

Since the symmetry energy effect depends sensitively on the isospin asymmetry of the participant region, we would expect that the transitional features shown in Fig. 5 depend on the size of the neutron skin and the beam energy. We thus examine the rapidity dependence of the π^-/π^+ ratio using

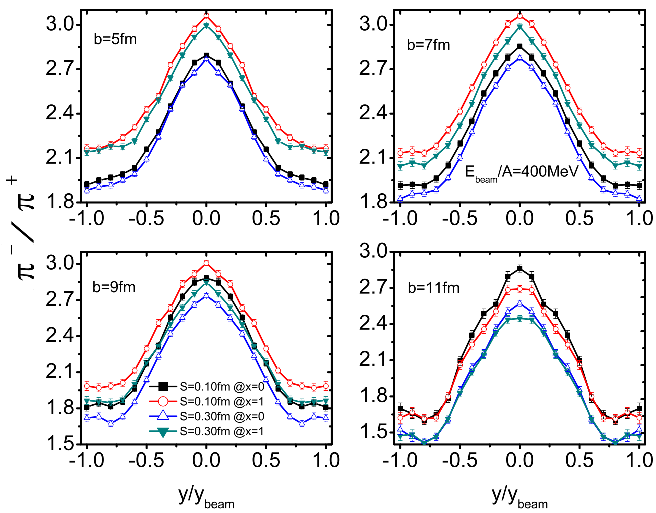

FIG. 6. (Color online) Rapidity distributions of the π^-/π^+ ratio from midcentral to peripheral Pb + Pb collisions at 400 MeV/nucleon with two sizes of neutron skin of 0.1 and 0.3 fm.

different sizes of neutron skin in ^{208}Pb in Figs. 6 and 7 with beam energies of 400 and 1000 MeV/nucleon, respectively. First of all, it is interesting to see again that in central reactions at both beam energies, the charged pion ratio is not much affected by the size of the neutron skin but is sensitive to the density dependence of the nuclear symmetry energy. However, the charged pion ratios in peripheral reactions are significantly affected by the size of the neutron skin. Moreover, it is seen that increasing the size of the neutron skin reduces appreciably the π^-/π^+ ratio in peripheral reactions, especially at a lower beam energy. Within the first-chance nucleon-nucleon collision model, without considering the isospin dependence of Pauli blocking as well as the subsequent pion reabsorption and reproduction that are modeled in the transport model, one natively expects the π^-/π^+ ratio to increase with the

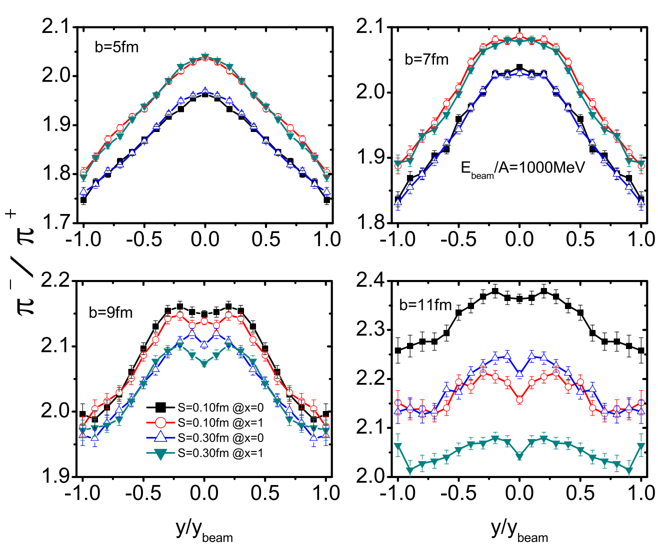

FIG. 7. (Color online) Same as Fig. 6 but for the beam energy of 1000 MeV/nucleon.

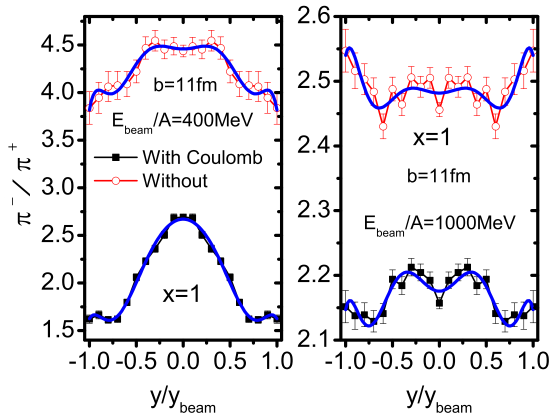

FIG. 8. (Color online) Rapidity distributions of the π^-/π^+ ratio with the soft symmetry energy ($x = 1$) in Pb + Pb collisions with an impact parameter of 11 fm and the beam energies of 400 and 1000 MeV/nucleon with and without the Coulomb fields, respectively. The blue (gray) lines are used to guide the eye.

increasing size of neutron skin. Indeed, this is observed in the earlier stage of the reaction. As shown in Fig. 4, with a thinner neutron skin the final multiplicities of both π^- and π^+ decrease in peripheral reactions because of the smaller overlap between the two colliding nuclei. However, the multiplicity of π^+ decreases faster than π^-, leading to a larger π^-/π^+ value for the reaction with a neutron skin thickness of 0.1 fm. Compared to the 400 MeV/nucleon case, the π^-/π^+ ratio at 1000 MeV/nucleon is flatter in rapidity y due to perhaps more production-reabsorption cycles that pions have to go through in the denser participant region formed at higher beam energies. Moreover, in peripheral reactions at 1000 MeV/nucleon the π^-/π^+ curve has a double bump structure. This is understandable since the nuclear stopping power is lower at 1000 than 400 MeV/nucleon. Thus, the Coulomb field of the spectators in peripheral collisions at 1000 MeV/nucleon leads to the well-known Coulomb peaks in the rapidity distribution of the π^-/π^+ ratio as shown in Fig. 8 by comparing simulations with and without including the Coulomb fields.

As shown in Figs. 6 and 7, while the absolute effect of the neutron skin is small, especially in central reactions, it is comparable or even larger than the effect due to the $E_{\rm sym}(\rho)$ in peripheral collisions, especially at 400 MeV/nucleon. Considering that one of the main interesting aspects of π^-/π^+ ratio is its sensitivity to the nuclear symmetry energy at suprasaturation densities in central heavy-ion collisions while in peripheral reactions it is sensitive to the size of the neutron

TABLE I. The measure $F(L_2)$ (10^{-2}) of the symmetry energy effect on the midrapidity π^-/π^+ ratio in Pb + Pb reactions.

	$S = 0.10$ fm	$S = 0.30$ fm
$E_{\rm beam}$(MeV)	400 (1000)	400 (1000)
$b = 5$ fm	13.7 (4.0)	12.2 (3.8)
$b = 7$ fm	11.4 (3.1)	10.4 (2.9)

TABLE II. The measure $F(S)$ (10^{-2}) of the neutron skin effect on the midrapidity π^-/π^+ ratio in Pb + Pb reactions.

	$x = 0$	$x = 1$
E_{beam} (MeV)	400 (1000)	400 (1000)
$b = 5$ fm	4.8 (0.4)	8.9 (0.2)
$b = 7$ fm	11.0 (0.4)	13.9 (0.9)
$b = 9$ fm	22.1 (7.8)	25.2 (7.2)
$b = 11$ fm	41.8 (20.6)	33.4 (18.5)

skin, we compare more quantitatively their relative effects on the π^-/π^+ ratio by using

$$F(L_2) = \frac{\Delta(\pi^-/\pi^+)}{\Delta L_2/L_2} \tag{4}$$

and

$$F(S) = \frac{\Delta(\pi^-/\pi^+)}{\Delta S/S}, \tag{5}$$

where $\Delta(\pi^-/\pi^+)$ is the resulting change in the midrapidity $(|y/y_{\text{beam}}| \leq 0.5)$ π^-/π^+ ratio due to the variation of L_2 or the size of the neutron-skin thickness S in the initial state. Obviously, for the considered reactions only with impact parameters less than about 7 fm, the central density can reach twice the normal density for a short time. We thus only show the $F(L_2)$ for central reactions in Table I. It is seen that the values of $F(L_2)$ are about the same with both $S = 0.1$ and 0.3 fm. They are indeed significantly larger than the corresponding values of $F(S)$ shown in Table II, indicating that indeed the π^-/π^+ ratio in these central reactions is an observable sensitive to the high-density symmetry energy with little influence from the uncertainties of the size of neutron skin. On the other hand, in more peripheral collisions the π^-/π^+ ratio is sensitive to the variation of neutron-skin thickness with small uncertainties due to our poor knowledge about the suprasaturation $E_{\text{sym}}(\rho)$, especially at lower beam energies. Moreover, we expect that pions with higher transverse momenta emitted from the skin-skin interaction region have more chances to escape. Shown in Fig. 9 is the transverse momentum dependence of the π^-/π^+ ratio in peripheral Pb + Pb collision with an impact parameter of $b = 11$ fm and a beam energy of 1000 MeV/nucleon. Indeed, the π^-/π^+ ratio with higher transverse momenta is more sensitive to the neutron-skin thickness in peripheral reactions.

IV. SUMMARY

In summary, the influence of the uncertainty of the neutron-skin thickness on the π^-/π^+ ratio in ^{208}Pb + ^{208}Pb collisions at beam energies of 400 and 1000 MeV/nucleon was examined within the IBUU11 transport model. While the neutron-skin

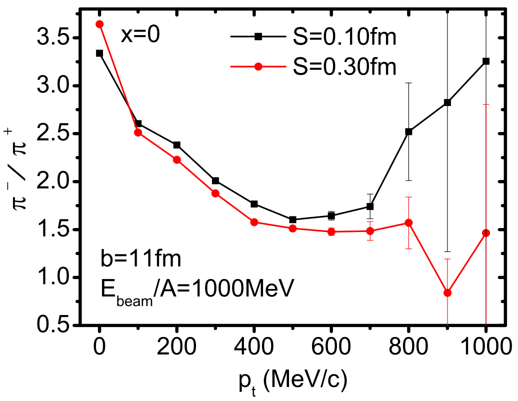

FIG. 9. (Color online) Transverse momentum dependence of the π^-/π^+ ratio with the stiff symmetry energy ($x = 0$) in Pb + Pb collisions with an impact parameter of 11 fm and a beam energy of 1000 MeV/nucleon with the two sizes of neutron skin of 0.1 and 0.3 fm, respectively.

effect on the π^-/π^+ ratio is negligible in central reactions at both energies, it increases gradually with increasing impact parameter and becomes comparable with or even larger than the symmetry energy effect in peripheral collisions especially at 400 MeV/nucleon. Moreover, it is found that while the π^-/π^+ ratio is higher with a softer $E_{\text{sym}}(\rho)$ in central collisions, above certain impact parameters depending on the size of neutron skin, a stiffer $E_{\text{sym}}(\rho)$ can lead to a larger π^-/π^+ ratio. Therefore, a clear impact parameter selection is important to extract reliable information about the $E_{\text{sym}}(\rho)$ at suprasaturation densities (size of neutron skin) from the π^-/π^+ ratio in central (peripheral) heavy-ion collisions.

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